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VENTILATORY DYNAMICS UNDER HYPERBARIC STATES

by

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ABSTRACT

Eleven U. S. Navy divers performed comparative dynamic pulmonary function tests under conditions of increasing density of the respiratory media. Variations in density and viscosity were produced by having the subjects breath air and helium-oxygen mixes in alternate studies while being subjected successively to 1 through 15 atmospheres absolute pressure. At 1 atm. abs. the predicted group mean MBC for air was 134.4 LPM; measured MBC was 180.1 for air, 228.4 LPM for 80% helium-20% oxygen. At 2 atm. abs. the MBC for air, was decreased below predicted normal but not until 6 atm. abs. did the MBC for helium-oxygen decrease below predicted normal. At 15 atm. abs. the MBC was decreased to 34.8% for air, 59.8% for HeO_2. The timed vital capacity curve showed a progressive flattening especially of the first second interval. The mean MEF (sustained 0.2 sec.) fell from 421 LPM to 140 LPM for air, and 548 LPM to 223 LPM for HeO_2 (80-20%)

Substitution of 95% helium-5% oxygen at 15 atm. abs. produced significantly less variation from normal in all parameters measured. Mean figures were 76.[illegible]% of predicted MBC, 70.9% first second TVC, and an MEF of 281 LPM. The increased work of breathing accompanying increased density of the respiratory media probably accounts for the relative decrease in RMV previously observed in underwater swimmers. High oxygen partial pressure, increased work of breathing and hypercapnia provide the ideal setting for oxygen toxicity. Helium-oxygen mixtures provide a more ideal respiratory media than nitrogen-oxygen mixtures for marked hyperbaric conditions, especially under circumstances requiring high flow rates and large respiratory minute volumes.

SUMMARY

The capacity of the ventilatory apparatus can be evaluated by the use of maximum effort dynamic ventilatory tests. These tests do not give a direct answer as to the response of the respiratory apparatus under a specific, submaximal stimulus but they do define the upper limits of ventilatory capacity. The maximum breathing capacity (MBC), timed vital capacity (TVC), and maximum sustained expiratory flow rate (MEF) are three such tests. Any factor which reduces the ability to perform these function tests can be considered to reduce the overall capacity of the composite respiratory apparatus. As density and viscosity of the respiratory media change one might expect an influence on the ventilatory capacity.

Eleven trained subjects, deep sea divers, were selected on the basis of normal pulmonary function. Their MBC, TVC, and MEF were compared at surface (1 atmosphere absolute) with performance of the same tests at increasing barometric pressure through 15 atmospheres absolute. A comparison was made between air and helium-oxygen mixtures as respiratory media.

There was a striking decrease in all parameters measured. The MBC mean decrease was 18.6% at 2 atmospheres, 44.2% at 6 atmospheres and 66.8% at 15 atmospheres while breathing helium compared to a much greater decrease while breathing air: 22.5% at 2 atm., 55.8% at 6 atm, a 75.8% at 15 atm. At 15 atmospheres with a mixture of 95% helium, 5% oxygen the mean percentage decrease in MBC was only 54.4%. The timed vital capacity was grossly altered, mainly as a reduction in the first second segment. Air produced a greater reduction than did helium-oxygen mixtures. The MEF was decreased to a mean of 140 LPM at 15 atmospheres with air and to a mean of 223 LPM with 80% helium-20% oxygen at 15 atmospheres.

The overall reduction in ventilatory capacity is probably the result of increasing density of the respiratory media with increasing barometric pressure, and is most likely mediated through increased turbulence of the gases in accordance with Reynold's number.

The influence of the increased work of breathing accounts for the previously observed decreased RMV and hypercapnia in underwater swimmers. This effect is potentiated by the high partial pressure of oxygen which exists during diving. There may be an additional role of the increased work of breathing, carbon dioxide retention, and high oxygen partial pressure in producing oxygen toxicity.

It is recommended that helium-oxygen mixtures be used instead of nitrogen-oxygen in mixed gas diving in order to decrease the work of breathing, provide better alveolar ventilation and decrease the danger of potential oxygen convulsions. Recommendation is made that further research be carried out to develop HeO_2 techniques and equipment, and to further evaluate the physiologic parameters of helium breathing as compared to other respiratory gases.

ADMINISTRATIVE INFORMATION

This study was conducted under Project NS 185-005 Subtask 5 Test 13 and is part of the overall effort of the U. S. Navy Experimental Diving Unit to contribute to the information on physiologic parameters of diving. Specifically, the tests are applicable to the use of various respiratory media in scuba and the capability of the respiratory apparatus during dives to great depths.

Work was begun on this study in October 1961 and was completed in March 1962.

ESTIMATED MANPOWER REQUIREMENTS

Description	Manhours
Diving	500
Data Handling	200
Literature Review and Writing	150
Drafting	10
Clerical	50
TOTAL	860 hrs.

This data was presented at the American Medical Association, Scientific Assembly, Section on Military Medicine, Joint Meeting with the Section on Diseases of the Chest, Chicago, Illinois, 27 June 1962.

The outstanding co-operation and efforts of LTJG Joseph L. REYNOLDS, MSC, USN and VAIL, John R., HMCA(DV), USN for their participation as testers in addition to their other duties is gratefully acknowledged. Special thanks are due all the divers and staff of EDU for their co-operation as subjects and chamber operators.

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1. INTRODUCTION

1.1 Background

1.1.1 The maximum breathing capacity (maximum voluntary ventilation), timed vital capacity, and maximum flow rates, as measures of dynamic pulmonary function, are reflections of the working limits, or ventilatory capacity, of the anatomical respiratory apparatus. These tests set the upper limit of the respiratory pump. Although the same level of function is seldom or never used in normal physiological requirements these measurements are useful tools in ascessing pulmonary function because a reduction in these parameters is almost certain to be reflected in any change in the efficiency of the composite apparatus. The techniques utilized in these dynamic measurements are simple and require relatively simple instrumentation in the clinical setting. The same is not true of many of the more complex, often confusing, performance measurements.

1.1.2 In addition to the intrinsic histo-pathological processes which may reduce the ability to move air into and out of the lungs, certain other factors internal and external to the subject may reduce the ventilatory capacity by influencing the airway resistance. Airway resistance is dependent not only upon the anatomical state of the conducting air passages but also upon the non-elastic resistance to air flow. In the completely healthy and fully co-operative subject the ventilatory capacity of the respiratory pump is almost wholly dependent upon the non-elastic airway resistance. Under these circumstances, airway resistance is [illegible] wholly dependent upon the sum of the product of the velocity of the respiratory media and the viscosity and density, respectively. The degree of airway resistance may be inferred by changes in the maximum breathing capacity, timed vital capacity, and maximum flow rates.

1.1.3 Deep sea divers have recognized for many years the subjective sensation of "thick" air and have commented upon the reduced ability to hyperventilate while breathing compressed air at several atmospheres ambient pressure. Many investigators have mentioned the probable reduction in ventilatory capacity due to the added work of breathing dense air. There appears to have been very little actual investigation of the physiological alterations produced by this phenomenon.

1.1.4 The mathematical expression, $\Delta P = K_1 (\dot{V}) + K_2 (\dot{V})^2$, as proposed by Rohrer, is most commonly accepted as representing the physiological flow conditions at one atmosphere absolute ambient pressure. In this formula ΔP is the expression of driving force producing air flow from a high to a low pressure, $\dot{V}$ expresses the velocity flow of the gases and K_1 and K_2 are, respectively, laminar and turbulent flow constants. In the suggested formula K_1, the constant for laminar flow, is the function of the viscosity of the gas whereas K_2 the constant for turbulent flow, is density dependent. It was originally assumed that the predominant flow pattern in the respiratory passages is laminar and that turbulent flow exists only at points of cross sectional change and normal anatomical airway irregularities. This assumption was probably erroneously drawn due to incorrect evaluation of velocity air flow in the air passages. It seems likely that the predomiant flow is turbulent and is present even in the straight air passages (3).

1.1.5 If healthy, physically fit subjects with a more than usual demand on their respiratory apparatus are subjected to changes in density and viscosity of the respiratory media one would expect to see a rather marked influence upon the capacity of the respiratory pump proportional in some manner to the degree of change and influenced by the velocity of air flow.

1.2 Objective

1.2.1 Because of the need for deep diving operations by the U. S. Navy and the need for heavy work capability necessitating large flow rates for adequate alveolar ventilation, it is important to know the limitations imposed upon and by the human respiratory apparatus under these conditions. Customarily, compressed air is utilized as a respiratory medium in dives to 200 ft. (7 atm. abs. pressure) and helium-oxygen mixtures are substituted below this depth because of the narcotic effect ascribed to nitrogen. We have little information on the effects of air or helium on the ventilatory dynamics below this depth and no comparison of the various media in the more shallow depths. Miles (1) reported mean percentage reduction in maximum breathing capacity of 51.7% at 200 ft. sea water equivalent depth, breathing air, a mean percentage reduction in MBC of 27.3% at 33 ft. (2 atm. abs.) and 48.9% reduction at 99 ft. (4 atm. abs.). No measurement of flow rates was made and there was no comparison with helium mixtures. He calculated a reduction in MBC of approximately 75% and 60% with air and with helium-oxygen (92-8%), respectively, at 594 ft. (19 atm. abs.). Marshall, Lanphier, and Dubois (2) found a linear decrease in the maximum expiratory flow rate with increasing depth despite a greater exerted ventilatory pressure at depth. Their observations were limited to three subjects at 4 atmospheres and one at 5 atmospheres.

1.2.2 Because of the need for further understanding of the relationship between increasing density of respiratory media and pulmonary ventilatory capacity and the need for guide lines in selection of respiratory media for both conventional deep diving and shallow diving with SCUBA equipment, the present study was undertaken.

2. METHODS AND PROCEDURES

2.1 Methods

2.1.1 Maximum breathing capacity (MBC), timed vital capacity (TVC), and maximum sustained expiratory flow rates (MEF) were performed by eleven male subjects using a 13.5 liter capacity Collins Respirometer installed in a U. S. Navy recompression chamber. The respirometer was fitted with 1.5 inch internal diameter smooth rubber hoses and a large bore directional breathing valve. The bell was chain balanced and since all the tests were of short duration, the internal valves and carbon dioxide absorption canister were removed in order to reduce inertia and obstructive resistance to a minimum.

2.1.2 The MBC was performed in the standard manner of maximum effort for fifteen seconds with the subject choosing his own rate and depth although the extremes of panting and of maximum vital capacity were avoided. The greatest result of duplicate or series tests was expressed in liters per minute. The timed vital capacity was performed in the standard manner utilizing the complete vital capacity and a maximally forced exhalation with a record paper speed of twenty-five millimeters per second. The maximum sustained expiratory flow rate was calculated by analyzing the expiratory volume flow curve for the maximum flow slope sustained over a two-tenths of a second interval.

2.1.3 A recorded output was obtained from a low mechanical resistance potentiometer attached to the respirometer pulley. This output was recorded by a Sanborn model 150 receiver-amplifier and variable speed, hot stilus recorder, outside the recompression chamber. The potentiometer output was calibrated for volume and speed of response against the recording pen of the Collins Respirometer preceding and following each testing period.

2.2 Procedure

2.2.1 The experimental design is shown in Figure 1. The subjects were selected on the basis of normal pulmonary function as determined by lung volumes and respiratory dynamics measured at one atmosphere ambient pressure with ambient air as the respiratory medium (Table 1). These tests were repeated several times and served to familiarize the subjects with the apparatus and developed a competitive atmosphere.

2.2.2 The comparative tests were conducted in five phases as outlined in Figure 1. The procedure was basically the same in each phase. The subject was comfortable seated in the recompression chamber with the tester acting as tender for the subject and making the necessary respirometer adjustments and manipulations. Air studies were conducted utilizing ambient chamber air following ventilation of the recompression chamber. The helium-oxygen mixtures for the subject and tender were supplied by demand regulators from outside the chamber through a reducing valve. At one atmosphere duplicate measurements of MBC, TVC, and MEF were made with the subject breathing air. The subject then breathed a helium-oxygen mixture (80%-20% respectively) for a minimum of seventy-five seconds in order to wash out the lungs. (This period of open circuit breathing was found to reduce the previously breathed inert gas to 5% or less residual end tidal fraction. Fractional exhaled gas percentages were determined by chromatography using a Beckman GC 2A gas chromatograph utilizing Argon as the carrier gas.) During this time the tester filled and flushed the respirometer several times with the HeO_2 mixture. The MBC, TVC, and MEF were then repeated in duplicate with helium oxygen as the respiratory medium. The chamber was then pressurized from the compressed air source at a rate of 3 to 5 atmospheres increase in pressure per minute. The subject and tester breathed chamber air during pressurization. In phase 1 the chamber pressure was leveled off at 4 atm. absolute where the measurements on air, lung wash-out and measurements on HeO_2 were repeated in the same manner as at 1 atm. abs. The chamber was then decompressed to 3 atm. abs. and the same order of testing repeated. The same procedure was followed at 2 atm. abs. Decompression was carried out according to standard U. S. Navy decompression tables and repeat measurements were made at 1 atm. abs. Phase 2 was identical to phase 1 except testing was carried out at 1 atm. and 5 atm. only.

2.2.3 At marked hyperbaric pressures, phase 3 and phase 4, a change in procedure was necessary to prevent the occurrence of nitrogen narcosis during pressurization. Previous studies at the Experimental Diving Unit have shown that performance is markedly impaired at high nitrogen partial pressure after only 2 to 3 minutes. Therefore, the subject was tested on HeO_2 (80%-20%) and then air at 1 atm. and at 9 and 15 atm. abs. in phase 3 and phase 4, respectively. During pressurization both the subject and tester breathed HeO_2 by open circuit demand system. Previous experience at this laboratory has shown no adverse electrocardiographic effect in suddenly switching from helium-oxygen to air as the breathing medium at 15 atm. abs. In phase 5 the oxygen percentage was reduced from

FIGURE [illegible]. EXPERIMENTAL DESIGN

1. Initial measurements for subject selection ambient air at 1 Atm. Abs. as respiratory media lung volumes, MBC, TVC, MEF

II. Moderate hyperbaric pressure

1. MBC, TVC, MEF - air
2. washout - 75 seconds
3. MBC, TVC, MEF He O_2 80 - 20%

Pressurization at 3 - 5 Atm./min. ambient chamber air as respiratory media

Standard Decompression

Phase 1) 4, 3, 2 Atm
Phase 2) 6 Atm.
1. MBC, TVC, MEF - air
2. washout - 75 seconds
3. MBC, TVC, MEF He O_2 80 - 20%

III. Marked hyperbaric pressure

1. TVC, MEF, MBC - air
2. washout - 75 seconds
3. MBC, TVC, MEF He O_2 80 - 20%

Pressurization at 3 - 5 Atm./min. He O_2 80 - 20% as respiratory media

Standard Decompression

Phase 3) 9 Atm Abs.
Phase 4) 15 Atm. Abs.
1. TVC, MEF, MBC - He O_2 80 - 20%
2. washout - 75 seconds
3. MBC, TVC, MEF - air

IV. Marked hyperbaric pressure (He O_2 95 - 5 %)

1. TVC, MEF, MBC - air
2. washout - 75 seconds
3. MBC, TVC, MEF He O_2 80 - 20%

Pressurization at 3 - 5 Atm./min. He O_2 80 - 20% as respiratory media

quick switch to He O_2 95 - 5% at 9 Atm. Abs.

Standard Decompression

Phase 5) 15 Atm. Abs.
1. TVC, MEF, MBC - He O_2 95 - 5%
2. washout - 75 seconds
3. TVC, MEF, MBC - air

TABLE 1 - VITAL STATISTICS OF SUBJECTS USED IN THIS STUDY*#

	Mean	S.D.
Age	32.8 yrs.	3.5
Height	69.7 in. (177.1 cm.)	2.3 (6.0)
Weight	169 lbs.	20
Body Surface Area	1.93 M^2	0.19

* N = 11

\# Ba[illegible]dwin, Cournand [illegible] [illegible]hards: Medicine, 27:243, 1948

20% to 5% for measurement at 15 atm. abs. This necessitated a switch from the 80%-20% HeO_2, on which the pressurization was begun, to 95-5% HeO2 during the pressurization. This was accomplished by a quick switch outside the chamber at a pressure of approximately 9 atm.

3. RESULTS

3.1 The vital statistics for the subject group are summarized in Table 1. The subjects consisted of 9 U. S. Navy enlisted men trained in deep sea and SCUBA diving assigned to the U. S. Navy Experimental Diving Unit and 2 U. S. Navy submarine and diving medical officers.

3.2 Table 2 shows the mean performance for the group at one atmosphere absolute with both air and HeO_2 (80-20%) as the respiratory media. The group was normal or better on all parameters of dynamic pulmonary function.

3.3 There was a reduction in all parameters measured with increasing barometric pressure. The subjects demonstrated marked respiratory work of all the inspiratory and expiratory muscles during these maximum effort tests. Figure 2 is a reproduction of a representative subject's recorded performance. The MBC tracing on the left shows, in addition to the reduced total volume of gas exhaled, a progressive change from rapid breaths of approximately 120 per minute and utilizing approximately half the vital capacity to a slower respiration, both inspiratory and expiratory, and a slight change in tidal volume. The right side of the figure shows a flattening of the timed expiratory curve to an obstructive pattern with increasing pressure.

3.4 Maximum breathing capacity

3.4.1 There was a progressive reduction in the actual measured MBC with increasing barometric pressure. Figure 3 gives a comparison of the percent decrease in MBC with air and HeO_2 (80-20%), respectively, as the respiratory media. The measurement at 1 atmosphere was considered to be 100%, i.e. no reduction. The rapid decrease in performance is apparent in the moderate range down to 6 atmospheres absolute (sea water equivalent depth of 165 ft.); however, the curve has not completely leveled off at 15 atmospheres. Surprisingly, the percentage decrease with HeO_2 is also very striking. Oxygen was felt to play a major role in this reduction; therefore, the studies at 15 atm. were repeated with the oxygen fraction in the helium mixture reduced to 5%. This improved the performance very significantly.

3.4.2 Because the performance on the HeO_2 mixture was so much greater than that on air at 1 atm., a comparison was made in the percentage of predicted MBC based on values predicted from body surface area and age, Figure 4. The mean for the group at 1 atm. was 135.1% of predicted normal on air and 171.5% of predicted normal on HeO_2. At 2 atm. the group mean was reduced to 88.3% predicted normal for air and remained well above predicted normal on HeO_2, 132.2%. Only when the pressure had been increased to 6 atm. abs. did the values on HeO_2 fall below 100% of predicted normal. At this depth the MBC values were 60.1% and 95.8% of predicted normal for air and HeO_2, respectively. At 15 atmospheres there was a significant reduction in both media, however 76.8% of predicted normal remained with HeO_2 95-5% as the respiratory medium.

TABLE 2 - MEASUREMENTS OF BASE LINE VENTILATORY DYNAMICS CONDUCTED AT SURFACE WITH COLLINS 13.5 LITER RESPIROMETER *

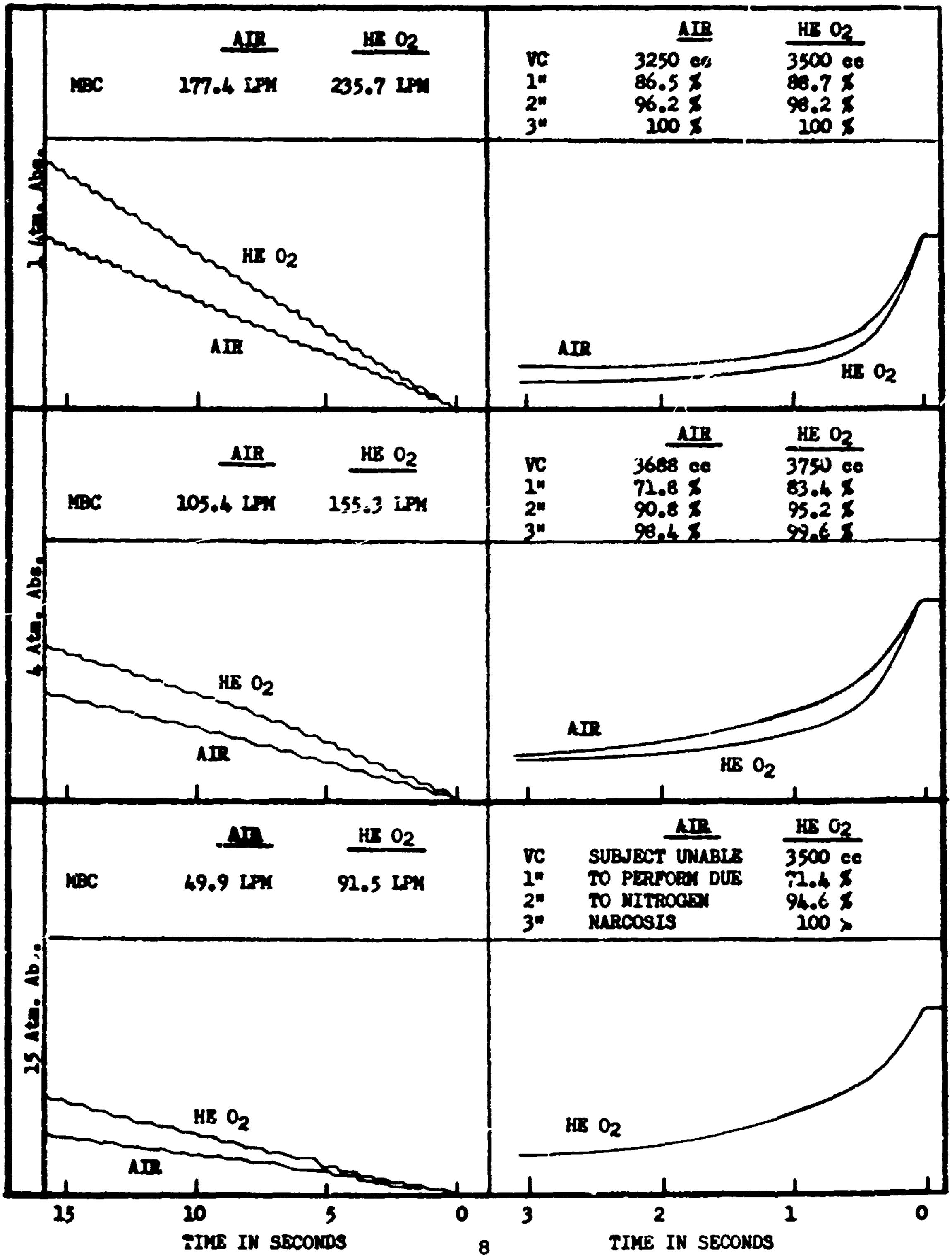
	Mean		S.D.
Predicted Surface M.B.C.	134.4	LPM	8.4
Measured Surface M.B.C. - Air	180.1	LPM	27.8
- HeO_2 (80%-20%)	228.4	LPM	36.0
Predicted Surface Vital Capacity	4246	cc	118
Measured Surface V.C. - Air	4240	cc	487
- HeO_2 (80%-20%)	4240	cc	485
Measured Surface M.E.F. - Air	420.6	LPM	54.6
- HeO_2 (80%-20%)	548.4	LPM	76.8

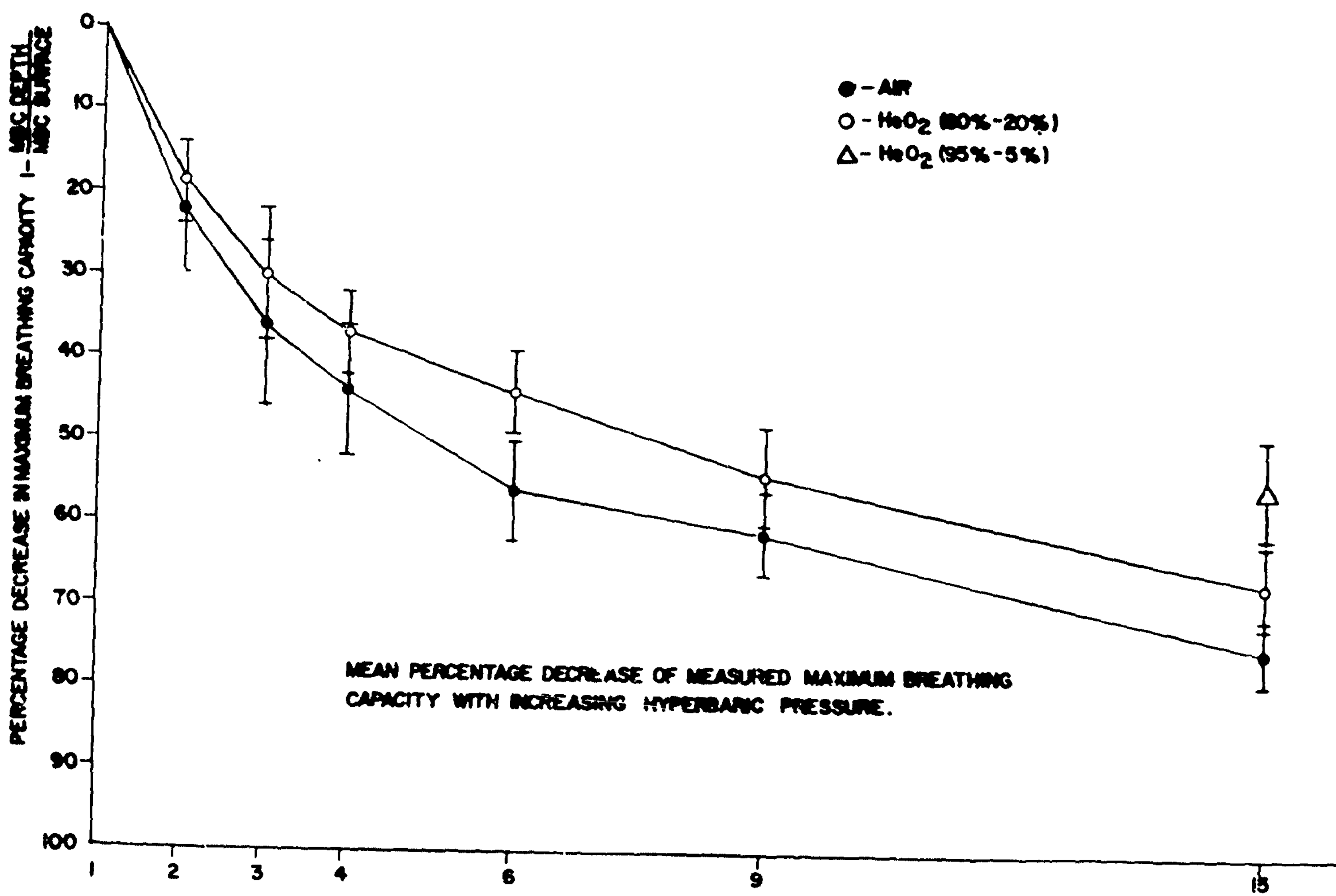
Measured Surface Timed Vital Capacity

	Air		HeO_2 (80%-20%)	
	Mean	S.D.	Mean	S.D.
1 second	81.2%	6.8	85.0%	5.8
2 seconds	92.3%	3.6	93.7%	3.4
3 seconds	96.4%	2.1	97.0%	2.2

* N = 11

FIGURE 2. REPRESENTATIVE TRACINGS
SUBJECT : D E K





● - AIR
○ - HeO_2 (80%-20%)
△ - HeO_2 (95%-5%)
MEAN PERCENTAGE DECREASE OF MEASURED MAXIMUM BREATHING CAPACITY WITH INCREASING HYPERBARIC PRESSURE.
PERCENTAGE DECREASE IN MAXIMUM BREATHING CAPACITY $1 - \frac{\text{MBC DEPTH}}{\text{MBC SURFACE}}$
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
6
9
15
DEPTH IN ATMOSPHERES ABSOLUTE

FIGURE 3.

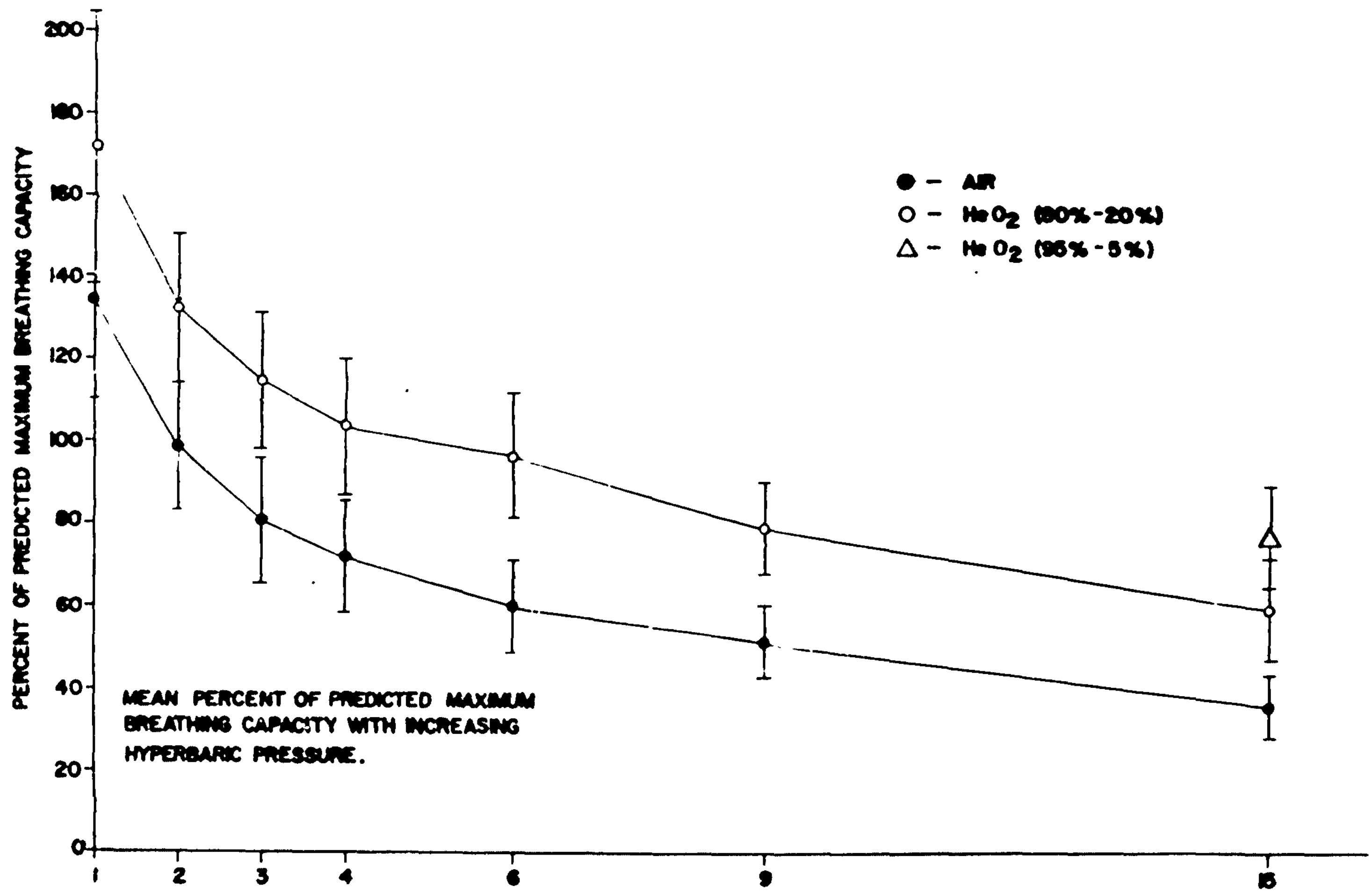


FIGURE 4. DEPTH IN ATMOSPHERES ABSOLUTE

3.5 Timed Vital Capacity

3.5.1 There was a marked reduction in each segment of the timed vital capacity especially in the 1 second interval, Figure 5. With the subject breathing air a definitely obstructive impairment is produced. This effect is evident even in the moderate range of hyperbaric pressure (less than 200 ft. sea water equivalent depth).

3.5.2 The three second timed vital capacity was less impaired, indicating a reduction in the peak expiratory flow rather than a reduction throughout the entire expiratory phase.

3.6 Maximum Expiratory Flow

3.6.1 The maximum expiratory flow was calculated from the highest rate of volume flow sustained for 0.2 sec. and is expressed in liters-per-minute flow. The values found at one atmosphere are well within normal range, Figure 6. Both media show a rapid reduction in flow with increasing density of the gases. However the helium-oxygen mixture produces a more favorable result than a comparable nitrogen-oxygen (air) mixture at all depths tested. With substitution of the 95-5% HeO_2 the flow rates remain near normal values for flow when compared with mid-expiratory flow while breathing air. The flow rate with 95-5% HeO_2 is slightly more than twice that of air when measured at 15 atmospheres.

4. DISCUSSION

4.1 The overall effect of the increase in barometric pressure was a depression in all measured parameters of dynamic pulmonary function with the development of an obstructive pattern. The most likely explanation for this finding is the increased airway non-elastic resistance secondary to the increased density of the respiratory gases. This resistance factor of density is most probably mediated through an increased turbulence. The decrease in observed performance is proportional to the increase in density though not in a linear manner.

4.2 Workman has predicted a decrease in MBC proportional to increasing density using the formula $1/\sqrt{\text{Density}}$. The graphic presentation of this predicted decrement curve is given in Figure 7. His figures agree fairly closely with our experimental findings. The two would perhaps fall more closely together had the same base line been used as reference. Workman assumed the hypothetical man to have 100% of predicted MBC on air and a greater than 100% of normal on HeO_2. Our subjects were actually found to have a greater than 100% predicted MBC breathing both air and helium-oxygen mixtures. Workman also calculated a decrement curve with the subject breathing a 92% helium-8% oxygen mixture whereas our subject breathed an 80% helium-20% oxygen mixture and at 15 atmospheres also breathed 95% helium-5% oxygen. Workman's calculations are very similar to Miles' (1) figures calculated utilizing respiratory gas of similar composition; however, Miles appears to have made an error in calculation at the lower pressures.

4.3 Mead (3) has shown, in actual measurements of resistance to breathing on a limited number of subjects at increased ambient pressure, that Rohrer's equation does not accurately predict the true effect of changing density and viscosity on turbulence. Indeed he proposes that Reynolds's

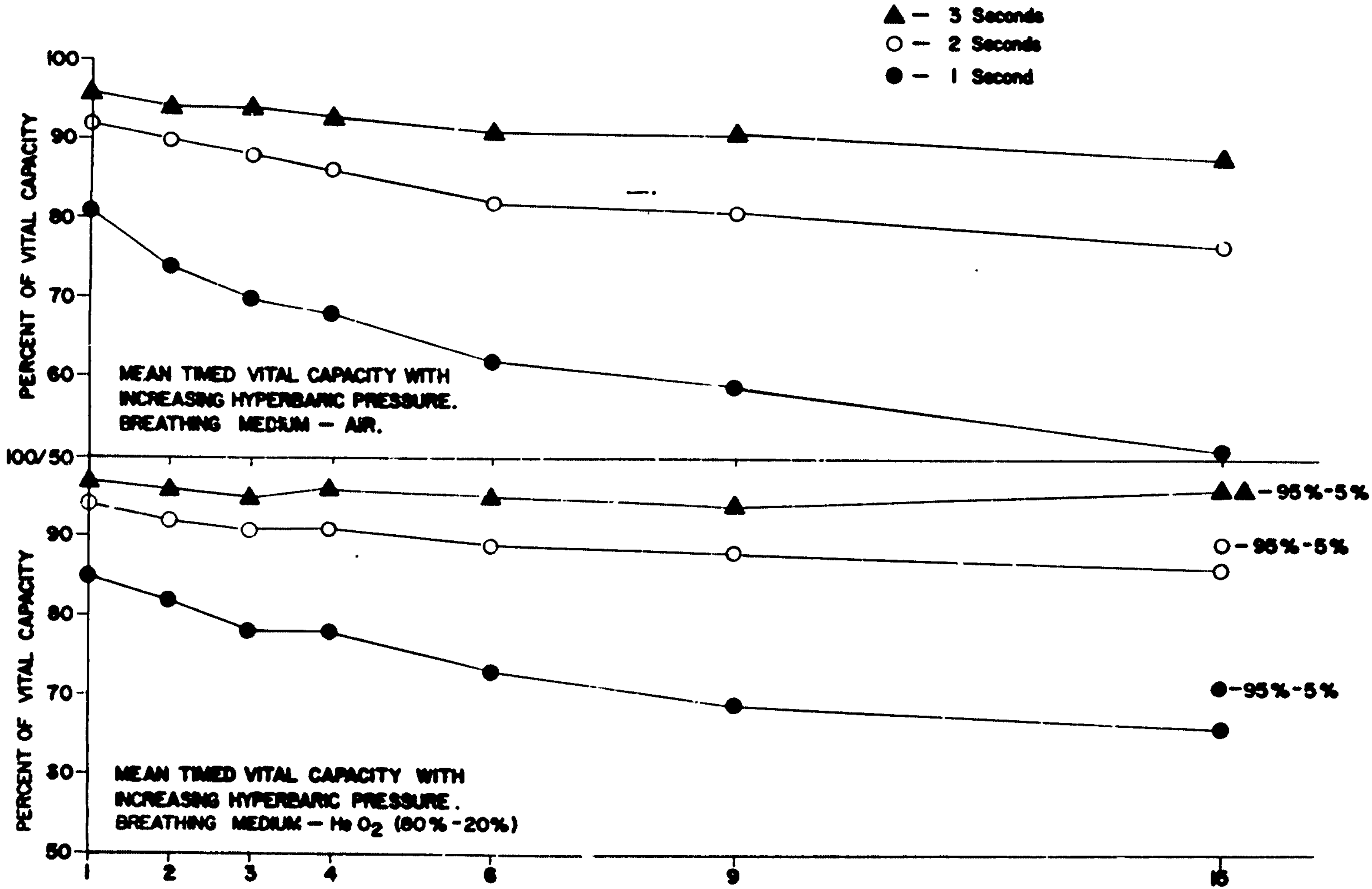


FIGURE 5. DEPTH IN ATMOSPHERES ABSOLUTE

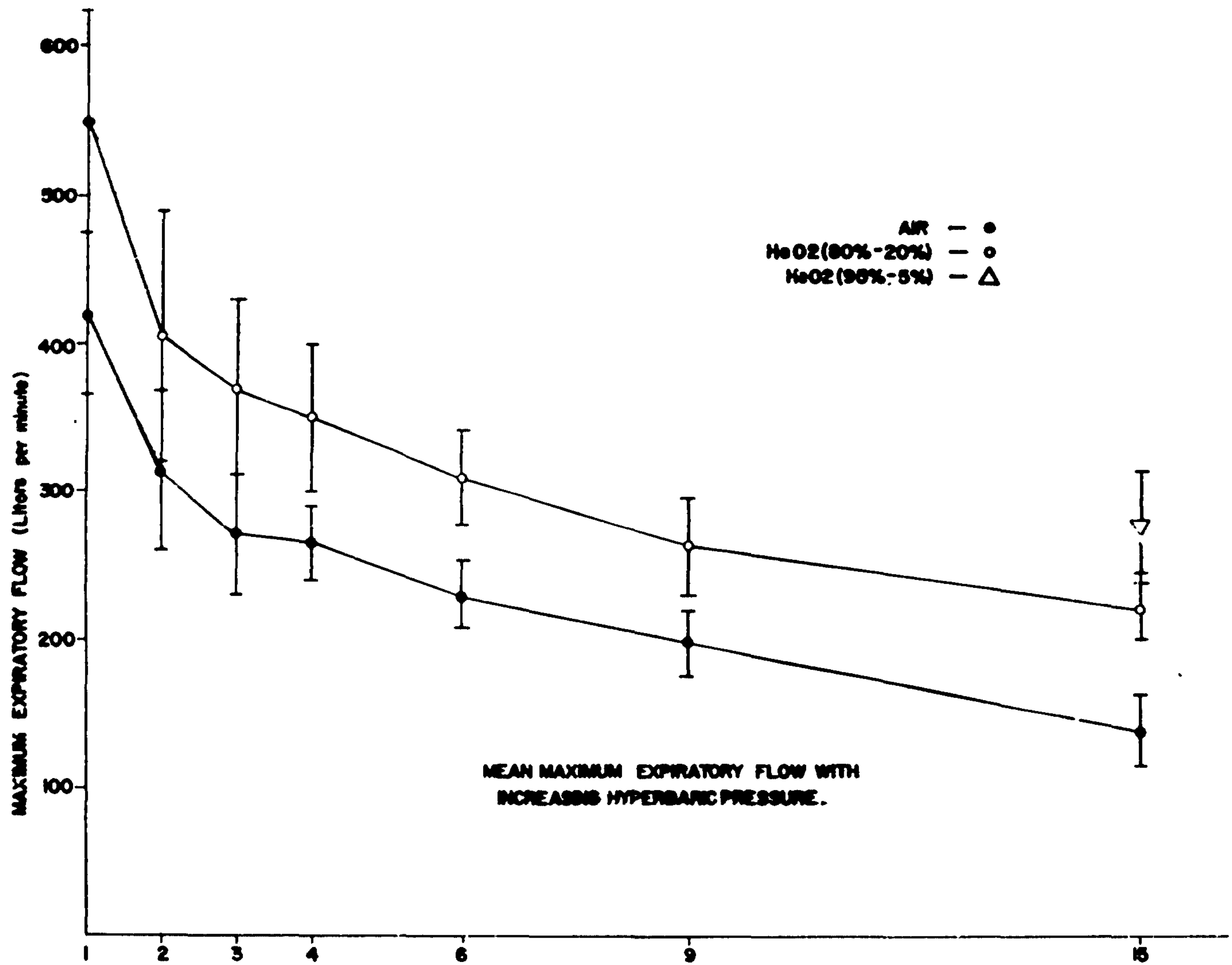
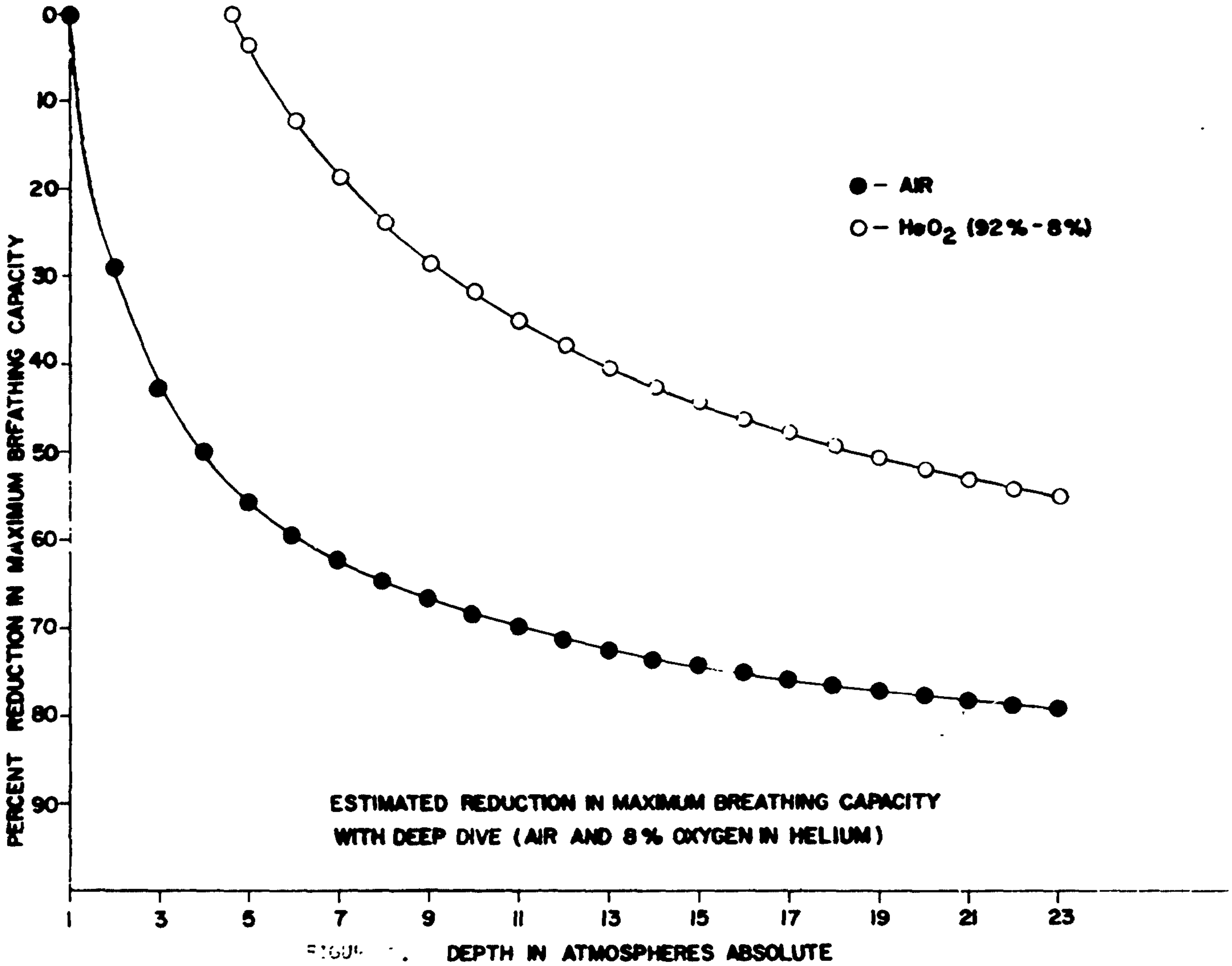


FIG. 6. DEPTH IN ATMOSPHERES ABSOLUTE



ESTIMATED REDUCTION IN MAXIMUM BREATHING CAPACITY WITH DEEP DIVE (AIR AND 8% OXYGEN IN HELIUM) number more adequately expresses the gas flow resistance in the respiratory tree. Resistance would then be directly proportional to the density and inversely proportional to the viscosity. With an increased density there would be increased turbulence, however with increased viscosity the turbulence would actually be decreased. The net effect then on resistance would be proportional to the ratio of density to viscosity, or to the kinematic viscosity.

4.4 In our study the major relationship seemed to be that of performance to density. In the helium studies the reduction in the percentage of oxygen, which is a dense gas, and increase in the helium fraction rather dramatically improved the performance. The effect of lowering the oxygen partial pressure on respiratory control cannot be excluded; however, since the effective oxygen partial pressure remained 75% of one atmosphere this seems less likely. The mean percentage figures for each of the media are given in tables 3A, 3B, and 4.

4.5 Lanphier (4,5) observed a decreased respiratory minute volume (RMV) and elevation of the alveolar and blood pCO_2 in underwater swimmers. He made observations on several subjects with varying respiratory media including oxygen, air, helium-oxygen (55-45%) and nitrogen-oxygen (55-45%) at increasing atmospheric pressure to 5 atm. abs. (132 ft. sea water equivalent). The decrease in RMV was greatest on air at 5 atmospheres but was decreased in proportion to the normal response expected for the observed alveolar pCO_2 in all instances. The exact etiology of this depression was unclear but depressive effects of nitrogen on the respiratory center and increased breathing resistance were suggested. It is unfortunate that mixtures of high oxygen content were selected for comparison since this produced a respiratory mixture of high density.

4.6 Interpreted in the light of presently existing data the finding of a decreased RMV in underwater swimmers breathing air or nitrogen-oxygen mixtures is not surprising. It is clear that the total work required for breathing is increased in terms of effort expended and oxygen consumed in performing respiratory work when breathing a gas of high density. If the efficiency of the respiratory muscles is comparable at hyperbaric states to that of the emphysematous patient, as is the alteration in the respiratory pattern, the oxygen requirement to move the same volume of air is greatly increased. Cherniack (6) has shown that in the emphysematous patient the oxygen cost of breathing may be as high as 19.5 ml. per liter of ventilation, or nearly 16 times the normal mean, and that mean efficiency of a similar group was 1.8%. He attributes this difference to a greater work load. Other investigators have shown similar figures for oxygen costs of breathing with slightly lower respiratory muscle efficiency. There can be no doubt that the work required for breathing is greater with increased density of gases. Mead (7) attributes a part of this increased work requirement to inertia of the air with increased ambient pressure

4.7 An apparent paradox exists. Even with the increased breathing resistance there appears to remain sufficient ventilatory capacity to meet the physiologic needs, at least for mild activity, yet the respiratory effort appears insufficient to produce adequate alveolar ventilation. As a consequency the alveolar pCO_2 is elevated to abnormal

TABLE 3 A - RESULTS OF MEASUREMENTS OF VENTILATORY DYNAMICS AT PRESSURES OF 1 - 15 ATMOSPHERES ABSOLUTE. BREATHING MEDIUM - AIR*

Depth in Atmospheres Absolute	Percentage Decrease in M.B.C.	Percent of Predicted M.B.C.	Timed Vital Capacity 1 sec.	2 sec.	3 sec.	M.E.F.	
1	-	135.1%	81.2%	92.3%	96.4%	421 LPM	Mean
	-	24.7	6.8	3.6	2.1	54.6	S.D.
2	22.5%	99.3%	73.9%	89.5%	94.3%	313 LPM	Mean
	7.8	14.7	9.5	4.7	3.3	54.9	S.D.
3	36.5%	81.0%	70.4%	87.5%	94.1%	271 LPM	Mean
	9.9	14.3	7.1	6.1	4.3	39.5	S.D.
4	43.8%	71.8%	68.1%	86.3%	93.2%	266 LPM	Mean
	8.5	13.0	6.4	5.0	4.0	25.1	S.D.
6	55.8%	60.1%	62.5%	82.4%	90.6%	230 LPM	Mean
	6.5	10 6	7.5	6.3	4.4	22.6	S.D.
9	60.6%	51.1%	59.4%	81.1%	91.3%	199 LPM	Mean
	4.6	8.6	7.4	7.2	4.6	21.6	S.D.
15	75.4%**	34.8%**	50.9%#	77.3%#	88.5%#	140 LPM#	Mean
	4.0	7.5	6.5	8.1	6.5	23.0	S.D.

* N = 11

** N = 10

N = 8

TABLE 3 B - RESULTS OF MEASUREMENTS OF VENTILATORY DYNAMICS
AT PRESSURES OF 1 - 15 ATMOSPHERES ABSOLUTE.
BREATHING MEDIUM - HELIUM OXYGEN (80%-20%)*

Depth in Atmospheres Absolute	Percentage Decrease in M.B.C.	Percent of Predicted M.B.C.	Timed Vital Capacity 1 sec.	2 sec.	3 sec.	M.E.F.	
1	-	171.5%	85.0%	93.7%	97.0%	548 LPM	Mean
	-	32.9	5.3	3.4	2.2	76.8	S.D.
2	18.8%	132.2%	81.6%	92.3%	95.9%	407 LPM	Mean
	5.3	18.0	6.2	4.2	3.0	84.2	S.D.
3	29.5%	114.8%	77.9%	90.8%	95.3%	370 LPM	Mean
	5.7	17.4	7.1	3.5	2.5	60.0	S.D.
4	36.6%	103.5%	78.2	91.4%	96.0%	351 LPM	Mean
	4.9	16.8	7.2	4.8	2.6	48.7	S.D.
6	44.2%	95.8%	73.3%	88.6%	94.6%	310 LPM	Mean
	5.2	15.3	9.1	5.8	3.7	32.4	S.D.
9	53.6%	78.8%	68.8%	87.5%	93.9%	264 LPM	Mean
	5.9	10.7	7.0	5.1	3.5	34.3	S.D.
15	66.8%**	59.0%**	66.1%**	85.8%**	96.4%**	223 LPM	Mean
	4.8	12.4	6.2	11.2	2.6	21.2	S.D.

* N = 11

** N = 10

TABLE 4 - RESULTS OF MEASUREMENTS OF VENTILATORY DYNAMICS AT PRESSURE OF 15 ATMOSPHERES ABSOLUTE. BREATHING MEDIUM - HELIUM-OXYGEN (95%-5%)*

	Mean	S.D.
Percentage decrease in M.B.C.	54.4%	6.0
Percent of predicted M.B.C.	76.8%	11.9
Timed vital capacity		
1 second	70.9%	8.2
2 seconds	89.7%	3.5
3 seconds	96.3%	2.6
Maximum expiratory flow	281 LPM	38.4

* N = 9

and even dangerously high levels. A comparable pCO_2 in the normal individual at 1 atmosphere absolute would evoke a maximum ventilatory response, near 75 to 100 LPM. In the underwater swimmer at increased barometric pressure however there is only a slight increase in the RMV. Several possible explanations exist. First, there may be an altered responsiveness to ventilatory stimuli due to the effect of increased barometric pressure per se. Secondly, the narcotic effect of the nitrogen may selectively depress the responsiveness of the respiratory center. Thirdly, the respiratory center may have adapted to a higher pCO_2. Lastly, factors not customarily considered of importance in respiratory regulation at 1 atmosphere may play a much greater role when the subject is exposed to hyperbaric pressure.

4.8 Zocche, Fritts, and Cournand (8) have shown that only about 50% of the MBC is available for prolonged hyperventilation and that this cannot be maintained over indefinite periods of time. If driven to the limit of capability the respiratory center responds by accepting a less than adequate alveolar ventilation in order to reduce the work. Cherniack and Snidal (9) and Eldridge and Davis (10) found this compromise between total work and accepted alveolar pCO_2 in otherwise normal subjects whose MBC had been decreased by artificial obstruction, but whose response of CO_2 inhalation fell far below the ventilatory capability. Zechman, et al (11) noted that graded airway resistance had only a small effect on respiratory flow rates in subjects at rest but during periods of greater ventilatory demands a dramatic effect on total flow restriction and alveolar gas composition was observed. There was a rising alveolar pCO_2 even though the respiratory apparatus was potentially capable of greater ventilatory response. The common factor in ventilatory responsiveness in each of these studies and the studies on emphysematous patients is the oxygen cost of breathing (12, 13).

4.9 The control of respiration, then appears not to be related to actual responsiveness to pCO_2 nor is it a reflection of mechanical limitation per se. Rather it seems to be related to the work required in breathing as measured by oxygen cost, that is the biological economy of the respiratory apparatus.

4.10 Lanphier's subjects demonstrated a more marked decreased responsiveness than might have been expected from the added work of breathing alone. This may have been due to the respiratory equipment used or may also have been due to the specific respiratory media used. In all instances the oxygen partial pressure was from 100% to 200% of one atmosphere. Normally, at 1 atmosphere absolute, the respiratory drive is relatively independent of the oxygen level except when the partial pressure falls well below one fifth of an atmosphere. High oxygen pressures in the normal individual has little if any effect, and if any effect is present, there may be a slight increase in the RMV, possibly due to irritation of the tracheo-bronchial mucosa by the dry oxygen or an increased alertness of the cerebral level. The effect of oxygen in depressing the respiration in patients with chronic pulmonary disease has been of interest since Beddard and Pembrey (14) published their observations in 1908. Studies by Richards, Fritts, and Davis (15) and by Brodovsky, Macdonnell, and Cherniack (16) indicate that the depression of respiration frequently observed in the emphysematous patient is usually dependent upon either a marked hypercapnia or hypoxia. Of greater significance in the respiratory response to high oxygen partial pressures is work of breathing and the total work being performed as demonstrated by Bannister and Cunningham (17) and by Lloyd, Jukes, and Cunningham (18). The effect of 100% oxygen on ventilation during exhaustive exercise was a decrease in RMV and rise in alveolar pCO_2. The presence of even a small decrease in alveolar pO_2 produced a greater increase in ventilation from a particular alveolar pCO_2 or from exercise.

4.11 When the work of breathing is increased, the presence of a normal or slightly decreased alveolar pO_2 may be of great importance. The removal of this stimulus by hyperoxia may play a very significant rôle in production of hypoventilation and hypercapnia. That this alteration in respiratory center does not require a prolonged period of adaptation but may be present within at least as short a time as thirty minutes has been demonstrated by Barnett and Peters (19).

5. CONCLUSIONS

5.1 The capacity of the respiratory apparatus is markedly diminished by an increasing density of the respiratory media but not in a linear fashion. The use of a gas with a high viscosity and low density greatly improves the capability of the respiratory pump.

5.2 The decreased capacity of the respiratory apparatus is probably the result of increased work of breathing produced by increased turbulence of the dense gases. Previously observed alterations in the RMV and hypercapnia in underwater swimmers at several atmospheres pressure can probably best be explained by the greater oxygen cost of breathing and the hyperoxic effect on respiratory control rather than by narcotic depression of the respiratory center by either nitrogen or carbon dioxide; at least early in the picture.

5.3 The significance of the decreased RMV and hypercapnia in the presence of hyperoxia as mediators of oxygen toxicity convulsions in underwater swimmers is not proven but seems highly probable. The use of helium-oxygen mixtures rather than nitrogen-oxygen mixtures as the respiratory medium in specialized underwater breathing equipment seems highly desirable.

5.4 Further investigation should be done to accomplish actual work of breathing measurements, CO_2 and O_2 response, and RMV and pCO_2 measurements under similar conditions. Work at this laboratory is presently being undertaken to further evaluate these parameters.

6. RECOMMENDATIONS

6.1 Nitrogen-oxygen mixture in scuba diving be abandoned and helium-oxygen mixtures be used exclusively in mixed gas scuba.

6.2 All dives in scuba apparatus which are greater than 100 ft. in depth and of sufficient duration so as to require decompression be made with mixed gas scuba apparatus.

6.3 Immediate investigation at EDU be directed toward development of HeO_2 decompression tables for mixed gas scuba.

6.4 Research into equipment design and engineering be initiated for the development of more satisfactory mixed-gas equipment.

6.5 Current research in underwater physiology be directed toward actual measurement of work of breathing, CO_2 and O_2 response, and RMV and pCO_2 measurements in a comparative study with air, N_2O_2, O_2 and HeO_2 and other combinations of these and other inert gases.

6.6 Concurrent observations be made of the relationship between the above factors and decompression, oxygen toxicity, oxygen consumption, and narcosis.

REFERENCES

1. Miles, S: The Effect of Increase in Barometric Pressure on Maximum Breathing Capacity, Medical Research Council, Royal Naval Personnel Research Committee, Report R.N.P. 58/922, (April) 1958

2. Marshall, R., Lanphier, E.H., and Dubois, A.B.: Resistance to Breathing in Normal Subjects During Simulated Dives, J. Appl. Physiol. 9:5-10, (July) 1956

3. Mead, J.: Resistance to Breathing at Increased Ambient Pressures, Proc. Underwater Physiology Symposium, National Academy of Sciences - National Research Council, (January) 1955, pp. 112-120

4. Lanphier, E.H.: Nitrogen-Oxygen Mixture Physiology
   I. Phases 1 and 2, Formal Report 7-55, (June) 1955
   II. Phase 3, Research Report 2-56, (August) 1955
   III. Phases 4 and 6, Research Report 7-58, (June) 1958
U. S. Navy Experimental Diving Unit, Washington 25, D. C.

5. Lanphier, E.H.: Use of Nitrogen-Oxygen Mixtures in Diving, Proc. Underwater Physiology Symposium, National Academy of Sciences - National Research Council, (January) 1955, pp. 74-78

6. Cherniack, R.M.: The Oxygen Consumption and Efficiency of the Respiratory Muscles in Health and Emphysema, J. Clin. Invest. 38:494-499, 1958

7. Mead, J.: Measurement of Inertia of the Lungs at Increased Ambient Pressure, J. Appl. Physiol. 9:208-212, (Sept) 1956

8. Zocche, G.P., Fritts, H.W. Jr., and Cournand, A.: Fraction of Maximum Breathing Capacity Available for Prolonged Hyperventilation, J. Appl. Physiol. 15:1073-1074, (November) 1960

9. Cherniack, R.M. and Snidal, D.P.: The Effect of Obstruction to Breathing on the Ventilatory Response to CO_2, J. Clin. Invest. 35:1286, 1956

10. Eldridge, F. and Davis, J.M.: Effect of Mechanical Factors on Respiratory Work and Ventilatory Responses to CO_2, J. Appl. Physiol. 14:721-726, 1959

11. Zechman, F., Hall, F.G. and Hull, W.E.: Effects of Graded Resistance to Tracheal Air Flow in Man, J. Appl. Physiol. 10:356-362, (May) 1957

12. Cournand, A., et al.: The Oxygen Cost of Breathing, Trans. Assoc. Amer. Physicians, 67:162, 1954

13. Campbell, E.J.M., Westlake, E.K., and Cherniack, R.M.: Simple Methods of Estimating Oxygen Consumption and Efficiency of the Muscles of Breathing, J. Appl. Physiol. 11:303, 1957

14. Beddard, A.P. and Pembrey, M.S.: Observations on Pulmonary Ventilation in Disease, Brit. Med. J. 2:580, 1908

15. Richards, D.W., Fritts, H.W. Jr., and Davis, A.L.: Observations on the Control of Oxygen on Ventilatory Response to CO_2 Inhalation, Trans. Ass. Amer. Physicians, 71:142, 1958

16. Brodousky, D., Macdonnell, J.A., and Cherniack, R.M.: The Respiratory Response to Carbon Dioxide in Health and Emphysema, J. Clin. Invest. 39:724, 1960

17. Bannister, R.G. and Cunningham, D.J.C.: The Effects on the Respiration and Performance during Exercise of Adding Oxygen to the Inspired Air, J. Physiol. (London). 125:118, 1954

18. Lloyd, B.B., Jukes, G.M., and Cunningham, D.J.C.: The Relation Between Alveolar Oxygen Pressure and the Respiratory Response to Carbon Dioxide in Man, Quart. J. Exp. Physiol. 43:214, 1958

19. Barnett, T.B. and Peters, R.M.: Studies on the Mechanism of Oxygen-Induced Hypoventilation, An Experimental Approach; J. Clin. Invest. 41:335-343, (Feb) 1962